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TES carbon monoxide validation during two AVE campaigns using the Argus and ALIAS instruments on NASA's WB-57F

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[1] The Aura Validation Experiment (AVE) focuses on validating Aura satellite measurements of important atmospheric trace gases using ground-based, aircraft, and balloon-borne instruments. Global satellite observations of CO from the Tropospheric Emission Spectrometer (TES) on the EOS Aura satellite have been ongoing since September 2004. This paper discusses CO validation experiments during the Oct-AVE (2004 Houston, Texas) and CR-AVE (2006 San Jose, Costa Rica) campaigns. The coincidences in location and time between the satellite observations and the available in situ profiles for some cases are not ideal. However, the CO distribution patterns in the two validation flight areas are shown to have very little variability in the aircraft and satellite observations, thereby making them suitable for validation comparisons. TES CO profiles, which typically have a retrieval uncertainty of 10–20%, are compared with in situ CO measurements from NASA Ames Research Center's Argus instrument taken on board the WB-57F aircraft during Oct-AVE. TES CO retrievals during CR-AVE are compared with in situ measurements from Jet Propulsion Laboratory's Aircraft Laser Infrared Absorption Spectrometer (ALIAS) instrument as well as with the Argus instrument, both taken on board the WB-57F aircraft. During CR-AVE, the average overall difference between ALIAS and Argus CO was 4%, with the ALIAS measurement higher. During individual flights, 2-min time-averaged differences between the two in situ instruments had standard deviation of 14%. The TES averaging kernels and a priori constraint profiles for CO are applied to the in situ data for proper comparisons to account for the reduced vertical resolution and the influence of the a priori in the satellite-derived profile. In the TES sensitive pressure range, ∼700–200 hPa, the in situ profiles and TES profiles agree within 5–10%, less than the variability in CO distributions obtained by both TES and the aircraft instruments in the two regions. TES CO is slightly lower than in situ measurements in the Houston area (midlatitudes) and slightly higher than in situ CO measurements in the Costa Rica region (tropical).

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1. Introduction

[2] Carbon monoxide (CO) is one of the most important compounds in the chemistry of the troposphere [*Holloway et al.*, 2000; *Logan et al.*, 1981]. It is the third most abundant carbon-based trace gas in the atmosphere, after carbon dioxide and methane (CH_4). The four major sources of atmospheric CO are fossil fuel combustion, biomass burning, oxidation of nonmethane hydrocarbons and oxidation of CH_4. Reaction of tropospheric CO with the hydroxyl radical (OH) accounts for most of the global CO sink, though CO is also lost via transport to the stratosphere and is also oxidized via biological consumption in soils [*King*, 1999; *Sanhueza et al.*, 1998; *Warneck*, 1988]. CO has an atmospheric lifetime on the order of months, dependent on latitude and season [*Hough*, 1991]. Because its lifetime is relatively short compared to the interhemispheric mixing time (1–2 years), CO is not thoroughly mixed throughout the troposphere. As a result, the CO global distribution closely resembles its source distribution [*Law*, 1999]. CO has the potential of indirectly controlling much of the oxidative capacity of the troposphere because OH is the only significant tropospheric sink for many other atmospheric trace gases emitted into the atmosphere [*Hewitt*, 1999; *Logan et al.*, 1981, and references therein]. CO can also be used to study transport in the troposphere since its

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relatively long lifetime in the upper troposphere permits long-range transport, making it a useful tracer of other pollutants [*Jost et al.*, 2004; *Stohl et al.*, 2002]. All the above make CO satellite validation important.

[3] The Tropospheric Emission Spectrometer (TES) on the NASA Aura satellite has been making CO measurements (derived from the nadir spectral infrared radiances) since September of 2004 [*Beer*, 2006; *Rinsland et al.*, 2006]. Efforts to validate TES CO data are summarized and updated in the TES Validation Report [*Osterman et al.*, 2006]. *Rinsland et al.* [2006] described the time trend for the performance of the TES instrument and the corresponding CO retrieval characteristics.

[4] The Aura Validation Experiment (AVE) is a series of field campaigns using aircraft, balloon and ground-based measurements to gather local atmospheric data that can be used to validate remote measurements taken from the Aura satellite. This paper describes TES CO validation efforts during two airborne campaigns using two different in situ instruments, Argus and ALIAS, on board NASA's WB-57F. The airborne campaigns include AVE October 2004 field campaign (referred to as Oct-AVE hereafter) and the Costa Rica Aura Validation Experiment (referred to as CR-AVE hereafter), which will be described in the next sections.

2. Oct-AVE 2004

[5] Oct-AVE was the first campaign in the AVE series. A series of eight science flights utilizing the WB-57F high-altitude research aircraft were conducted in late October and early November 2004. The WB-57F was configured with a suite of eight in situ and three remote sensing instruments to collect data on atmospheric gases (such as CO, ozone, CH_4, and water vapor), aerosols, and cloud physical properties. Flights were based out of Ellington Field, Houston, Texas (29°N, 95°W). The mission objectives included validation of instruments on the Aura satellite, including validation/calibration of TES instrument. This was accomplished by WB-57F underflights of the Aura satellite over open water and clear sky conditions, as well as underflights during satellite overpass of radiation ground sites.

3. CR-AVE 2006

[6] CR-AVE was a mission designed to explore the tropical upper troposphere and lower stratosphere (UT/LS) and to provide information for comparison to satellite observations. The tropical region between 30°N and 30°S comprises half of the Earth's surface, yet has been relatively unsampled in comparison to the midlatitude of the Northern Hemisphere. In addition, observations above typical aircraft altitudes (12 km) are even less frequent, making the tropical upper troposphere and lower stratosphere one of the most sparsely sampled regions of our atmosphere, which provided the impetus for the CR-AVE campaign.

[7] Satellites have provided a wealth of information on the tropics. However, validation information was required in order to prove that the satellite data is sufficiently accurate for scientific research, especially considering how sparsely sampled the tropics have been. Aircraft observations were particularly necessary to provide an independent test of the satellite observations. Unfortunately, because of limited number of aircraft flights and the validation needs for all four Aura instruments (TES, MLS, HIRDLS and OMI), the available TES and in situ observation comparison pairs are relatively far apart. The comparison validations are still valuable because the Costa Rica region is not near the CO emission source regions and the TES observations show rather uniform distributions in the aircraft flight area.

[8] Flights on the WB-57F were based out of Ellington Field, Houston, Texas (29°N, 95°W), and San Jose, Costa Rica (10°N, 84°W). Eleven of the twelve science flights were conducted in a rectangular region within 10°N to 2°S, 78°W to 88°W. One science flight sampled air as far north as 17°N.

4. Instrumentation Descriptions

[9] CO measurements on the WB-57F during both Oct-Ave and CR-AVE were collected with NASA-Ames Research Center's tunable diode laser spectrometer, Argus, which has been described in detail elsewhere [*Loewenstein et al.*, 2002] and will only briefly be described here. The Argus instrument is a small, lightweight, dual-channel instrument capable of measuring atmospheric mixing ratios of CO and CH_4 every 2 s. Argus is an absorption spectrometer operating in rapid scan, second-harmonic mode using modulated, tunable diode lasers operating at 2111.5 cm^{-1} for detection of the CO $P(8)$ absorption line. Spectra are coadded for 2 s and are stored on a solid state disk for later analysis. It is a fully autonomous instrument that can cycle between atmospheric measurement and calibration. In each channel, a laser beam traverses a multipass Herriott cell, for a total path length of 36 m in the cell. Instrument calibration is completed both in the laboratory and during flight using calibrated whole air gas standards provided by the National Oceanic and Atmospheric Administration Global Monitoring Division (NOAA GMD). In addition to strong absorbing lines, the spectral regions were chosen near spectral absorbers, which can be used as a frequency marker in a reference cell. The postflight data reduction routine involves fitting spectra (nonlinear least squares Marquardt-Levenberg) to the second Fourier component of the modulated Voigt absorption line shape [*Reid and Labrie*, 1981]. The accuracy of measured CO, to one-sigma, is approximately 3% with a long-term precision value (over 5–6 h) of near 2 ppb for CO.

[10] During CR-AVE, CO measurements on the WB-57F were also collected with Jet Propulsion Lab's ALIAS instrument. The Aircraft Laser Infrared Absorption Spectrometer (ALIAS) [*Webster et al.*, 1994] is a four-channel, tunable laser spectrometer configured during CR-AVE to measure CO, CH_4, nitrous oxide, total water and total water isotopes. Inlet air is heated to ~293 K then analyzed in a temperature-monitored, multipass Herriott cell with 80-m optical path length operating at ambient pressure. For CO, the $R(5)$ line of the fundamental at 2165.60 cm^{-1} is scanned at 20 Hz by emission from a DFB quantum-cascade laser. Scans are coadded and written to disk every 2.2 s. Similar to Argus, second-harmonic detection of modulated signals is employed. During flight, a reference cell is placed in the path of the laser beam to calibrate emission frequency with respect to laser current. Short-term (2 s) precision (1σ) is

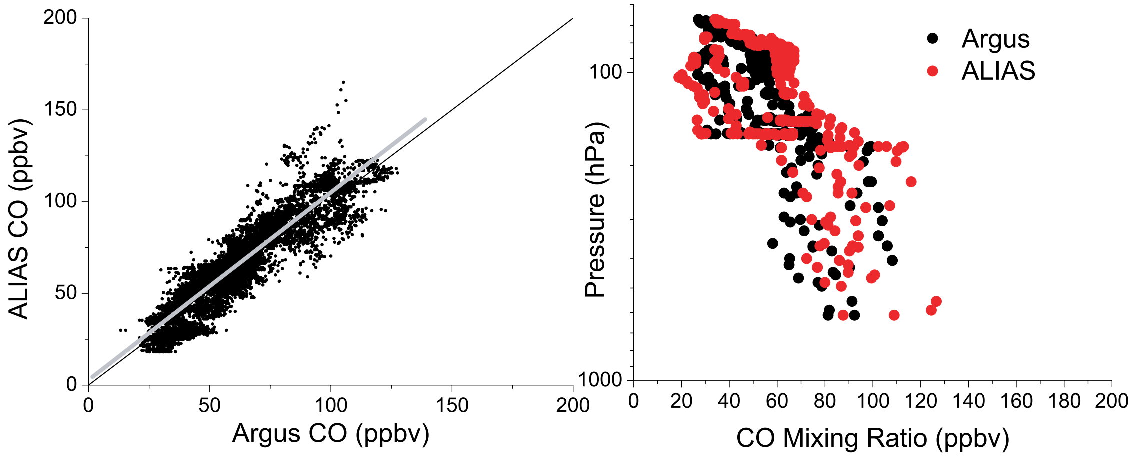

Figure 1. (left) Linear correlation plot of Argus and ALIAS data for 2006 CR-AVE campaign. Thin line is 1:1 line. Thick gray line is linear fit with R = 0.92, slope = 1.02, and intercept = 2.8 ppbv. (right) Vertical profiles of Argus (black dots) and ALIAS (red dots) 2-min-averaged data during the CR-AVE mission.

better than 0.2 ppbv. Accuracy, which includes the uncertainty of the gas standard, is estimated to be 3%, including instrument drift (mainly in optical alignment). The second-harmonic signal was calibrated prior to the mission and recalibrated once, with the same standard, during the mission. The same standard was used for periodic checks of instrument performance throughout the mission, which found that instrument drift was less than a few percent.

[11] TES is an infrared Fourier transform spectrometer with a high spectral resolution of 0.06 cm^{-1} on board the NASA-Aura satellite launched 15 July 2004 [*Beer*, 2006; *Beer et al.*, 2001]. TES makes Global Survey (GS) measurements at nadir every other day ($\sim$26 h continuous operation) and makes special observations, e.g., Step and Stare (SS) or transect, along a portion of the satellite orbit in the GS "off" orbits via scheduled requests. The nadir footprint of TES is 5 $\times$ 8 km, separated by $\sim$550 km (before May 2005) or $\sim$180 km for GS, and separated by 42–46 km for SS. TES CO retrieval uses small spectral windows in the CO (0–1) band and is performed after the atmospheric temperature, water and ozone retrieval steps. The volume mixing ratio profiles of CO are estimated together with surface temperature and emissivity, and a layer of effective cloud by minimizing the measured and the modeled spectra with a priori constraints [*Bowman et al.*, 2006; *Kulawik et al.*, 2006]. The time trends of TES instrument performance and the CO retrieval sensitivity and error breakdowns are presented by *Rinsland et al.* [2006]. In the work by *Luo et al.* [2007a], comparisons of global CO fields between TES and MOPITT are performed and the influence of the a priori and the instrument characteristics on the data products and comparisons is addressed. In the work by *Luo et al.* [2007b] TES CO profiles are compared with measurements from another in situ instrument, DACOM on board DC-8 during INTEX-B Houston phase in March 2006. Averaged TES CO was found to be <10% less than the adjusted DACOM CO.

[12] Like retrievals from all remote sensing instruments, TES CO profile retrievals have limited vertical resolution. Although TES reports species volume mixing ratios at $\sim$25 levels between surface and 100 hPa, these values are correlated. The degree of freedom (DOF) of the signal for a TES CO profile describes the vertical resolution of the retrieved profile [*Rodgers*, 2000]. In the area of and during the AVE campaigns, the DOFs for TES CO are 1–1.5, which means that TES CO profiles have 1 to 1.5 pieces of independent information vertically.

5. Argus-ALIAS Intercomparison

[13] The Argus and ALIAS instruments have flown together on several airborne campaigns, including CR-AVE, AVE-WIIF(Aura Validation Experiment–Water Isotope Intercomparison Flights), Pre-AVE (Pre-Aura Validation Experiment), CRYSTAL-FACE (The Cirrus Regional Study of Tropical Anvils and Cirrus Layers–Florida Area Cirrus Experiment), and SOLVE (SAGE III Ozone Loss Validation Experiment). During the CR-AVE mission, Argus and ALIAS measured CO simultaneously on six flights. Figure 1 shows the intercomparison between ALIAS and Argus CO, on CR-AVE flights when coincident data was collected, regardless of whether the flights were used for TES validation. For data averaged over 120 s, the standard deviation of the difference between the instruments was 14%. The overall difference between the instruments, averaged over the entire campaign, was 4%, ALIAS being higher. As Figure 1 demonstrates, both in situ instruments observe a decrease in CO above 100 mbar which is in contrast to the a priori profile used by TES during CR-AVE.

[14] Argus and ALIAS each claim $\sim$3% instrumental accuracy which includes instrument bias separate from gas standards. It is noted that both Argus and ALIAS utilize CO standards provided by NOAA GMD and that the uncertainty (1σ) of both cylinders is $\sim$2% [*Novelli et al.*, 2003; P. C. Novelli, personal communication, 2007]. The quadrature sum of individual accuracies and uncertainty in CO cylinder content is $\sim$5% (1σ) and can explain the campaign-averaged bias between ALIAS and Argus. The long-term differences observed during CR-AVE are larger than expected given their stated accuracies and precision. Though side-by-side comparison in the lab using the same CO standard gas has

Table 1. TES and Argus Comparison Information for the Oct-AVE Campaign: Oct-AVE Step and Stare Colocations Between Argus and TES

	Date				
	31 Oct	3 Nov	5 Nov	7 Nov	9 Nov
Number of Argus profiles	3	3	3	2	3
Distance range between TES and Argus (km)					
Takeoff	560–100	160–170	130–20	410–270	700–420
Landing	560–100	160–170	130–20	410–270	700–420
Spiral	10–15	130–150	60–150		20–200
Time between TES and Argus (hours)					
Takeoff	2.0	2.5	1.9	2	3
Landing	2.5	2.2	2.7	2.5	1.7
Spiral	0.5–1.5	0.4–1.0	0.4–1.3		–1.0

not been performed, reasons for these differences are being investigated by both instrument teams.

6. Comparisons Between Satellite-Retrieved Profiles and the in Situ Measurements

[15] There are three issues that need to be addressed in validating satellite retrieved species profiles with in situ measurements. The first is to identify profile pairs that are close both in distance and in time. Although AVE campaigns are designed for Aura profile validations, only limited number of aircraft profiles can specifically be identified for TES CO validations. We included profiles taken during the takeoff and landings that normally covered more than a couple of hundred kilometers horizontally. The variabilities for both in situ and the selected TES profiles are calculated, which provide the upper limit for the biases between the in situ and TES values. In the analysis for this manuscript, the distance between TES and in situ profiles are indeed large (e.g., >500 km) for half of the cases. However, if the variability of the CO fields within the region of a few hundred kilometers is reasonably small (e.g., background CO), the comparisons are still valuable. We based the descriptions of the CO distribution for the regions used in this study on TES and MOPITT daily/monthly maps that are available online at http://tes.jpl.nasa.gov/gallery/LEVEL3_PLOTS/R10/MonthlyMean/browse_MonthlyMean.cfm and http://mopitt.eos.ucar.edu/mopitt/data/plots/mapsv3_mon.html respectively.

[16] The other two issues involve finding a proper way to compare in situ profiles and satellite retrieved profiles which differ in (1) vertical resolution and (2) in the use of a priori information (in the case of the satellite). *Rodgers and Connor* [2003] and *Luo et al.* [2007a] described the proper comparison process and examples in detail. TES retrieval CO profiles (X_{ret}) can be approximated by the combination of the true profile (X) vertically smoothed by the averaging kernel (A) and the a priori profile weighted by $(I - A)$, X_a:

$$X_{ret} = AX + (I - A)X_a + \varepsilon \qquad (1)$$

where ε is the retrieval error due to noises in the radiance measurements and the forward model errors. The X, X_a and X_{ret} profiles are given at pressure levels and the A is the averaging matrix given in pressure by pressure. For the comparisons presented in this paper, we assume the in situ profile as the true, X, and derive X_{ret}, the simulated TES retrieved profile via equation (1). In this process, the in situ profile is vertically smoothed by the averaging kernel and biased by the a priori, X_a in levels where no information can be obtained from TES measurements. This derived profile is compared to the corresponding TES retrieval. In pressure levels where TES retrievals are dominated by the a priori, we will see nearly perfect agreement in the comparison. In pressure levels where TES measurements are sensitive to the CO distributions, ~700–200 hPa, the in situ measurements provide valuable validation for the TES retrievals.

[17] There are cases where the aircraft covered limited vertical ranges, e.g., 600 hPa and above, which is the third problem in the comparisons. The entire profile, X, is needed to derive X_{ret} at any given level in equation (1). We use TES a priori profile, X_a, scaled at the bottom of the aircraft profile to extend the aircraft profile downward. Xa is the best climatology for CO in the region for this purpose.

7. TES-Argus Intercomparison in Oct-AVE

[18] During Oct-AVE, TES made routine GS Measurements and scheduled SS measurements typically on TES validation WB-57F flight days. Table 1 illustrates the WB-57F flights that were designated TES validation flights. There was a total of 18 aircraft CO profiles with takeoffs, landing and spirals. Up to six TES profiles closest to the aircraft profiling area were selected to compare with each in situ CO profile resulting in a total of 43 TES validation profiles. The spirals were typically coordinated (both in time and geolocation) for the best direct in situ intercomparison between a TES overpass and a WB-57F flight. The TES CO retrievals near these spirals typically had degrees of freedom of 1.1 to 1.3.

[19] Figures 2 and 3 illustrate the WB-57F flight paths and the TES Step and Stare nadir measurement locations on two separate flight days, 31 October and 9 November, during Oct-AVE. The vertical profiles studied are shown in green for each of those flight days. These two flights are selected to demonstrate retrieval results indifferent air masses sampled over the Gulf of Mexico and inland over the Southern United States.

[20] The flight on 31 October focused on validation of the TES instrument. The aircraft took off heading east to intercept the Aura ground track (near the Louisiana-Mississippi border), and then south (at 18 km altitude) across the Gulf of Mexico. At the time of the Aura overpass, the WB-57F

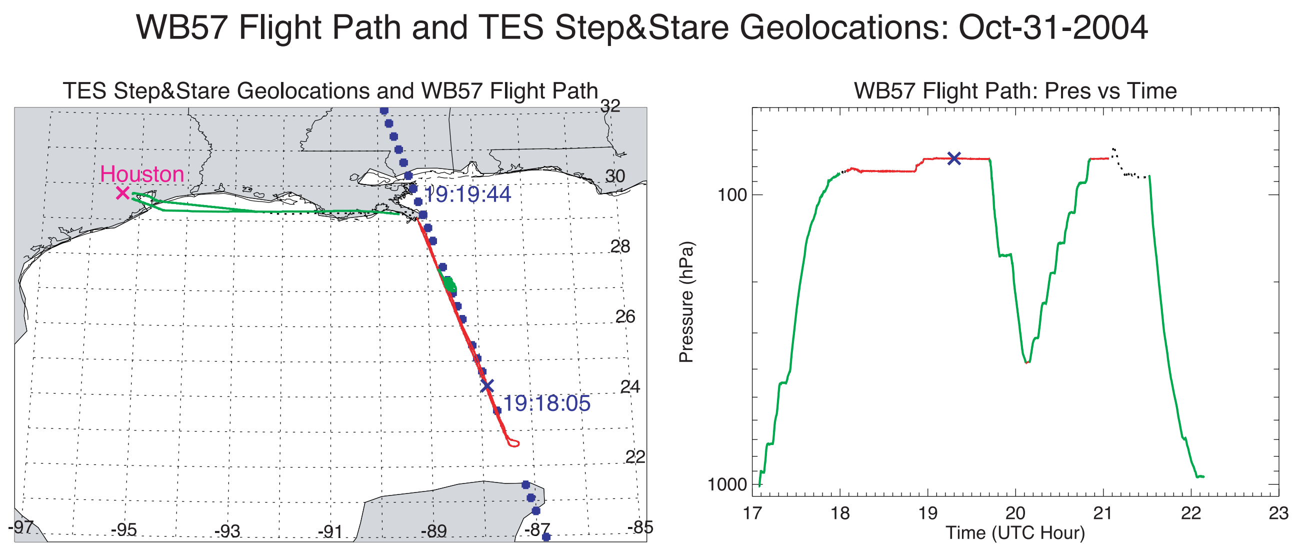

Figure 2. WB-57F flight path and TES Step and Stare geolocations for 31 October 2004, in the Gulf of Mexico. (left) The red line indicates the WB-57F flight path, the blue circles are TES nadir observation geolocations, and the blue crosses are for when the WB-57F and TES coincide in time. (right) The green lines represent the four vertical profiles (ascent, descent, and spiral), which can be used for TES comparison. The data from the spiral are used in the comparison shown in this paper.

was headed north after turning near Mexico's Yucatan Peninsula. Following the Aura overpass, the aircraft executed both a spiral down (to 7.6 km) and a spiral up. The maximum altitude for the flight was 18.6 km. The weather over the flight track contained large cloud-free areas and some areas of low (below 1.5 km) scattered clouds. The sampled air was taken in relatively cloud free regions (TES retrieved effective cloud optical depth <0.1). The DOF for the signal for TES CO retrievals is 1.3.

[21] The WB-57F pressure time series for 31 October is shown in Figure 4. Argus CO mixing ratio time series is overlaid on that same plot. The spiral descent and ascent are contained between the black dashed lines (Figure 4, top left), which corresponds to the Aura TES nadir overpass of the WB-57F. Only the data in the spiral ascent and descent are used for this comparison. CO as a function of pressure is shown in Figure 4 (top right). The pressure time series of the Argus CO along the TES track is shown in Figure 4 (bottom left). This is converted to an Argus CO curtain plot of pressure versus latitude (Figure 4, bottom right). This can be used to compare to a TES curtain plot (not shown for this flight). For the spiral, there were three TES profiles that could be chosen for the intercomparison with the black tick mark on top of Figure 4 (bottom right) showing the closest profile.

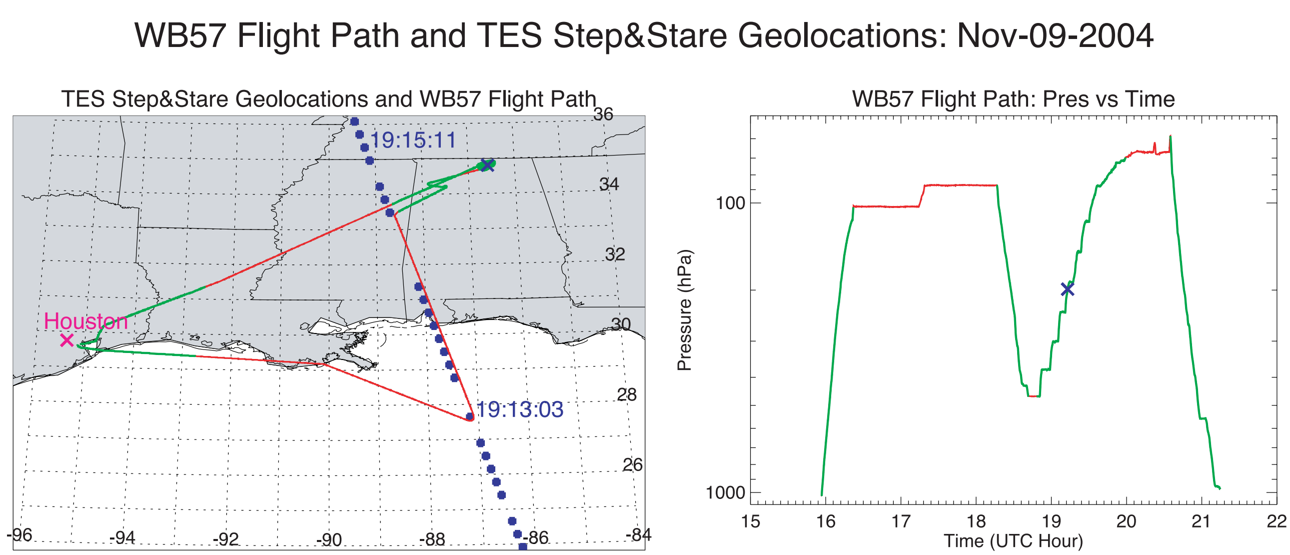

Figure 3. WB-57F flight path and TES Step and Stare geolocations for 9 November 2004, over the southern states. The color scheme is the same as those described in Figure 2. The data from the spiral are used in the comparison shown in this paper.

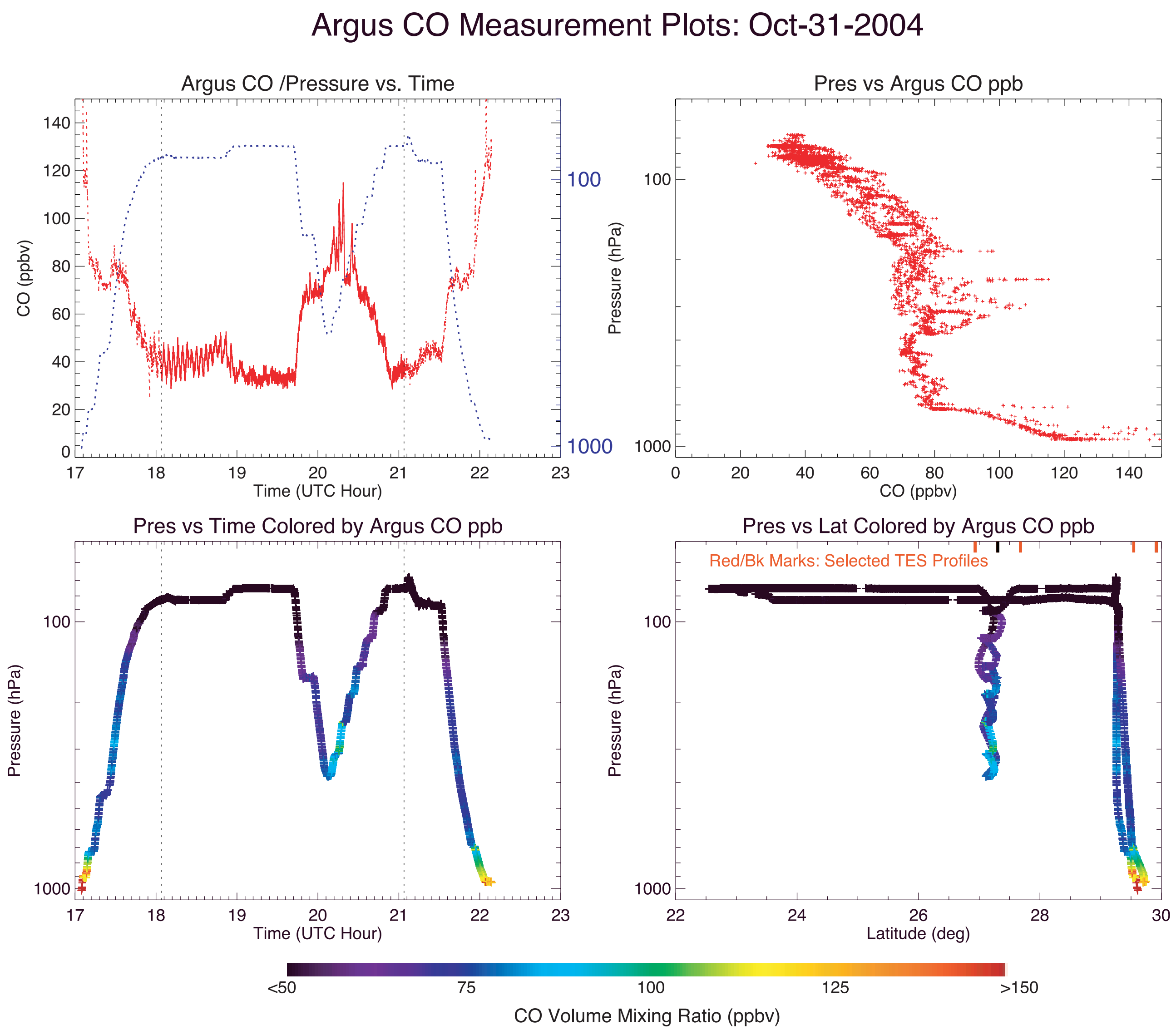

Figure 4. WB-57F Argus measurements of CO for 31 October 2004 flight near Houston. (top left) The CO time series overlaid with the pressure of the WB-57F aircraft, (top right) the Argus CO as a function of pressure overlapping with TES geolocations, (bottom left) the Argus CO as functions of time and pressure, and (bottom right) the Argus CO as functions of latitude and pressure. The red/black marks on Figure 4 (bottom right) are the TES profile locations used to compare with the two Argus CO profiles, respectively (black being the TES profile closest in distance to the averaged Argus locations).

[22] The vertical profile of Argus CO has a higher vertical resolution than the TES retrieved CO represented by 1.3 DOF (Figure 5). This makes a direct comparison incorrect. In addition, TES retrieves CO to the ground while the aircraft spiral only descended to approximately 400 hPa. TES retrieval CO profiles (X_{ret}) can be approximated using equation (1). Figure 5 shows an example of the TES and Argus CO profile comparison. Figure 5 (top left) shows the Argus CO vertical profile during the spiral, TES a priori CO profile, and the selected TES CO profiles with retrieval errors. The TES averaging kernels at 3 pressures are shown in Figure 5 (top right). In the process of comparing Argus CO to the TES profile, the Argus profile is extended to the surface and upward via scaled TES a priori profile to match the Argus CO values at its bottom and top pressures. This Argus profile is then treated as the true profile, X in the above equation. The new X_{ret} for Argus CO is calculated.

[23] The CO Argus profile, with the TES averaging kernel and a priori profile applied, is seen in Figure 5 (bottom left). Figure 5 (bottom right) shows percent difference between the TES profiles (from the three closest TES profile locations) and the Argus profile with the averaging kernel applied. The noticeable changes in the original and the adjusted Argus profiles are the vertical gradient and the in situ values in <150 hPa shifted to the TES a priori. These are due to the influence of the TES a priori.

[24] A similar analysis was done for the flight of 9 November whose objective was to obtain remote sensing observations for TES SS observational points in a latitudinal profile from Gulf of Mexico to Alabama-Mississippi border. The

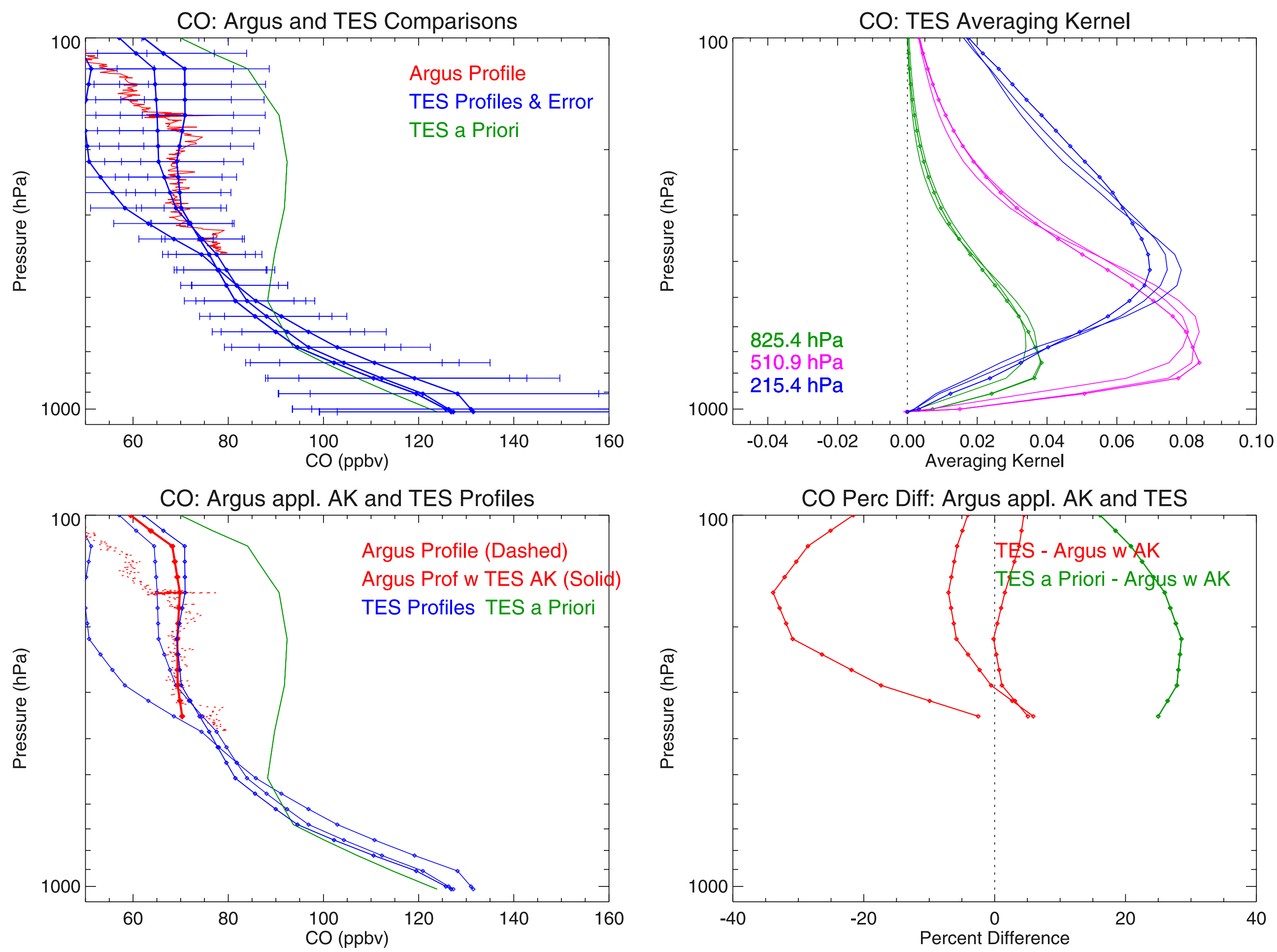

Figure 5. An example of TES and Argus CO profile comparisons. The CO profiles were taken over the Gulf of Mexico on 31 October 2004. (left) The Argus CO values (red) were sampled in the spiral down. The three closest TES CO retrieved profiles near the Argus profile are shown for comparisons (blue). (top right) The TES averaging kernels corresponding to three sample pressures. (bottom right) The percent difference in CO profiles between TES and Argus, where the Argus profile is the one after applying TES AK and the a priori profile.

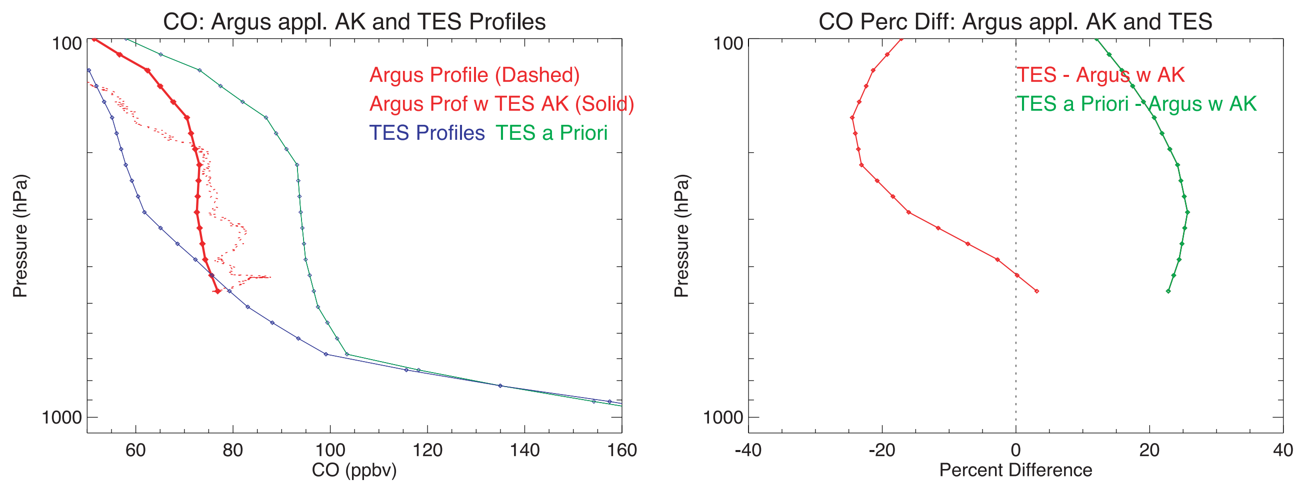

Figure 6. Argus and TES ascent profiles for the 20041109 flight. (left) The blue solid line is the TES profile. The green line is the a priori profile. The red dotted line is the in situ high-resolution Argus CO profile and the red solid line is the Argus profile with the averaging kernel applied to the data. (right) The percent difference between the Argus profile with averaging kernel applied and the TES profile (in red) and the percent difference between Argus profile with averaging kernel applied and the TES a priori profile (in green).

WB-57F flew along the Aura suborbital track over the Gulf of Mexico to a point near the Mississippi-Alabama border. The WB-57F then turned northeastward and descended to 6 km feet over Huntsville, Alabama. Then a spiral ascent (from 6 km to 17 km) was flown over Huntsville. This flight corresponded to a land-based source region for CO. This analysis of the spiral is shown in Figure 6. Only the closest TES profile location is shown. The agreement between the Argus CO profile and the TES CO profile is poorer than the 31 October case. This was the worst case for the Oct-AVE campaign among all the TES-Argus comparisons we examined. The TES CO retrieval profile was lower than the Argus profile in mid to upper troposphere.

[25] Figures 7 and 8 show the comparison statistics between Argus and TES for the entire Oct-AVE campaign. To remove the a priori dominating cases, we use the criterion

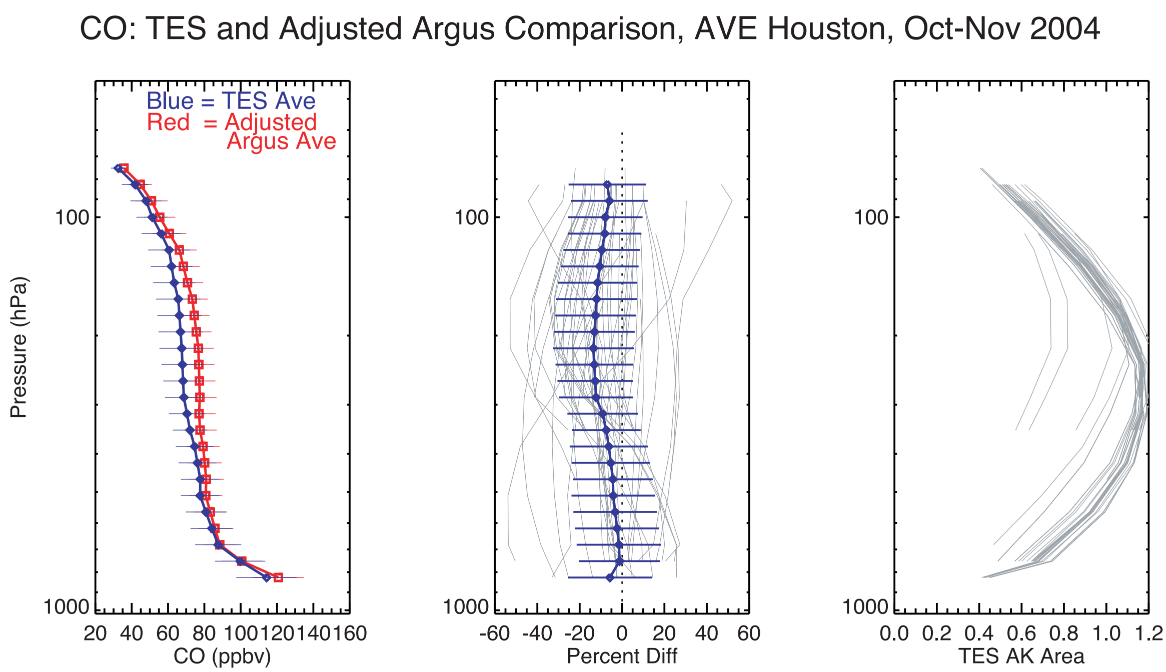

Figure 7. (left) Averaged Argus and TES CO and (middle) the percent difference profiles for entire Oct-AVE campaign. (right) The areas of the TES averaging kernels. TES and Argus CO value comparisons are selected for AK area greater than 0.4. In Figure 7 (left), the standard deviations for TES and adjusted Argus CO comparison pairs are also shown. The blue profile in Figure 7 (middle) is the average calculated as (TES-Argus)/Mean * 100 and their standard deviations.

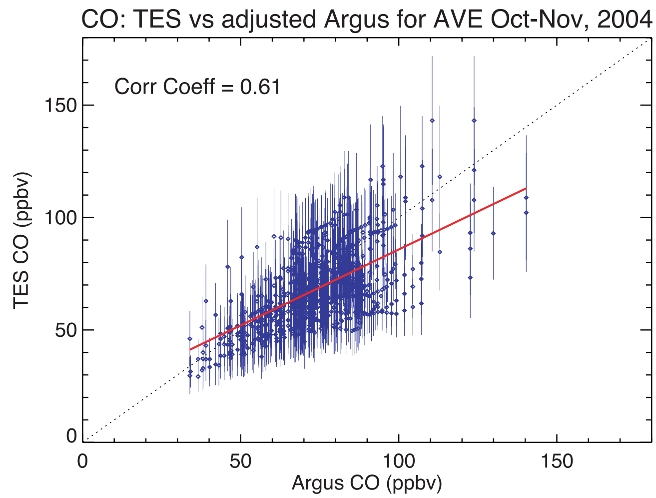

Figure 8. Argus-TES correlation plot for CO volume mixing ratios at all pressures taken Oct-AVE during October–November 2004. Comparison data are selected for TES averaging kernel areas (Figure 7) less than 0.4. Red line is a linear fit to the data. Dotted line is one-to-one line.

based on the averaging kernel area [*Rodgers*, 2000] from TES retrievals. The TES-Argus comparison pairs are removed from the statistical analysis if the averaging kernel area is less than 0.4. On average TES CO profiles are found to be slightly lower than the Argus CO profiles. The differences between Argus and TES CO profiles, however, are within TES retrieval errors (10–20%) and equivalent to CO spatial and temporal variability (~20%) detected in both TES and Argus profiles. Overall Argus and TES agree within 5–15%. The correlation coefficient for all Oct-AVE flights was found to be 0.61. Without dropping those insensitive profile points (where AK is less than 0.4), mostly in the upper and lower troposphere, the correlation coefficient was 0.78. These correlation factors are for all the profiles and all the layers. This conclusion is in good agreement with TES-DACOM comparisons of CO profiles during INTEX-B 2006 campaign [*Luo et al.*, 2007b].

8. TES-Argus-ALIAS Intercomparison for CR-AVE

[26] During CR-AVE, TES made routine GS measurements and a few SS measurements typically on TES validation WB-57F flight days. Table 2 illustrates the WB-57F flights used here as TES validation flights. There was a total 15 aircraft CO profiles counting takeoffs, and landings in San Jose, Costa Rica. Unfortunately, there were no spirals coordinated with TES overpasses, therefore the only vertical profiles available were all upon takeoff and landing in Costa Rica. Typically these were neither temporally nor spatially coordinated with TES. We examined TES daily and monthly CO distribution patterns in the troposphere (http://tes.jpl.nasa.gov/gallery/level3Plots.cfm). Because the Costa Rica area is far away from the globally noticeable CO emission sources in January–February 2006 and the CO distribution in the area shows very little variability, we consider these comparisons valuable for TES CO validations in the tropics regions.

[27] There were two different instruments on WB-57F measuring CO during this campaign, with ALIAS measuring throughout both the remote and in situ portions of CR-AVE and Argus measuring during the in situ portion of the campaign. The remote portion of the campaign (flights 20060114 to 20060127) occurred in the early portion of the mission and contained primarily remote sensors. The in situ portion of the campaign (flights 20060130 to 20060211)

Table 2. TES and WB-57F Comparison Information for the CR-AVE Campaign: CR-AVE Colocations Between TES and the WB-57F[a]

	Date							
	17 Jan	22 Jan	25 Jan	30 Jan	1 Feb	7 Feb	9 Feb	11 Feb
Number of ALIAS (Argus) profiles	2	2	2	2 (2)	2 (2)	2	2 (2)	1 (1)
Distance between TES and WB-57F (km)								
Takeoff	390	160	965	1062	1042	84	87	542
Landing	536	43	1146	1180	1045	105	185	
Time between TES and WB-57F (hours)								
Takeoff	1	1	1	10	3	3	13	12.5
Landing	2.5	3	2.5	11	0.5	1	9	
ALIAS measurement	x	x	x	x		x	x	x
Argus measurement				x	x		x	x

[a]This table includes information on which in situ instrument acquired CO data during the flight. Crosses indicate the flights where each instrument (ALIAS and Argus) was measuring data.

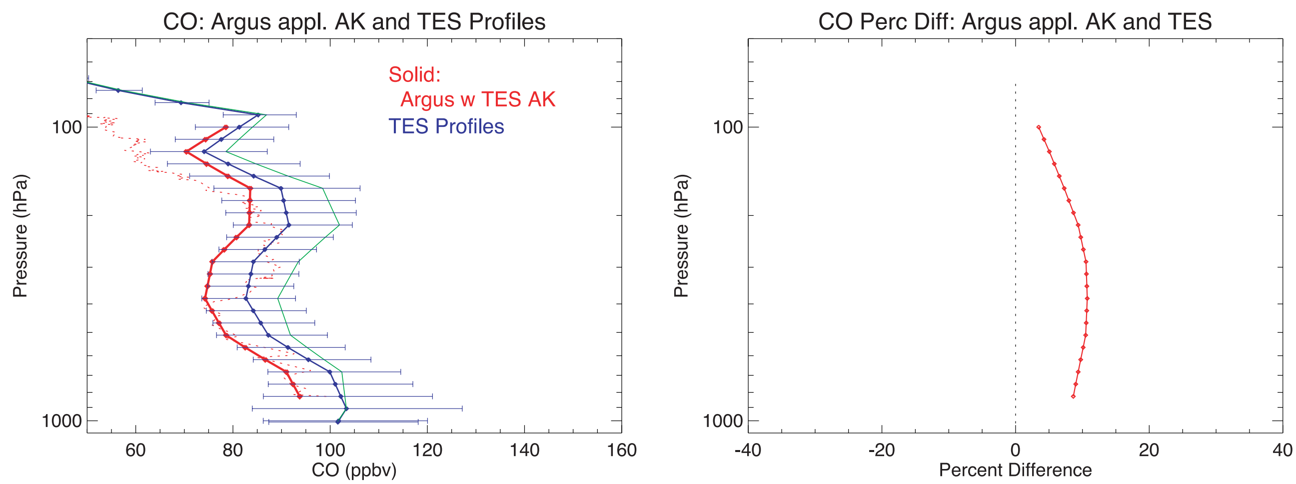

Figure 9. Argus and TES ascent profiles for the 20060201 flight. (left) The blue solid line is the TES profile with its errors. The green line is the a priori profile. The red dotted line is the in situ high-resolution Argus CO profile and the red solid line is the Argus profile with the averaging kernel applied to the data. (right) The percent difference between Argus profile with averaging kernel and the TES profile.

occurred in the latter portion of the mission and contained primarily in situ sensors. There are three flights used in this validation study where both in situ instruments measured CO simultaneously.

[28] During the in situ portion of the campaign, there were six Argus CO profiles used for comparison. None of the Argus CO profiles had good coincidences with TES CO profiles, being far away either temporally (>1 h) or spatially, with TES overpasses between a few hundred to over a thousand kilometers away. We will discuss two case studies for Argus: one with TES close temporally but far away spatially (1 February, takeoff) and one with TES close spatially but far away temporally (9 February, takeoff). The case of 9 February is a flight day where ALIAS was also measuring CO.

[29] Figure 9 shows the comparison plots of Argus CO profile and TES CO retrieved profile for 1 February takeoff. The analysis of this flight was done in a similar fashion as for the Oct-AVE campaign. The TES effective optical depth for takeoff was 0.2 demonstrating relatively cloud free conditions. The Argus profile, shown here, was taken during takeoff, 1042 km from the closest TES CO profile, which was separated by 3 h from the Argus measurements. The Argus CO profile is lower than both the TES a priori and the retrieved CO profiles, with an exception between 200 and 400 hPa. The application of the TES a priori and averaging kernels to the Argus high vertical resolution profile adjusts its vertical shape. This adjusted Argus profile is 5–10% lower than the TES retrieved profile. This is within the retrieval errors of TES. The disagreement between

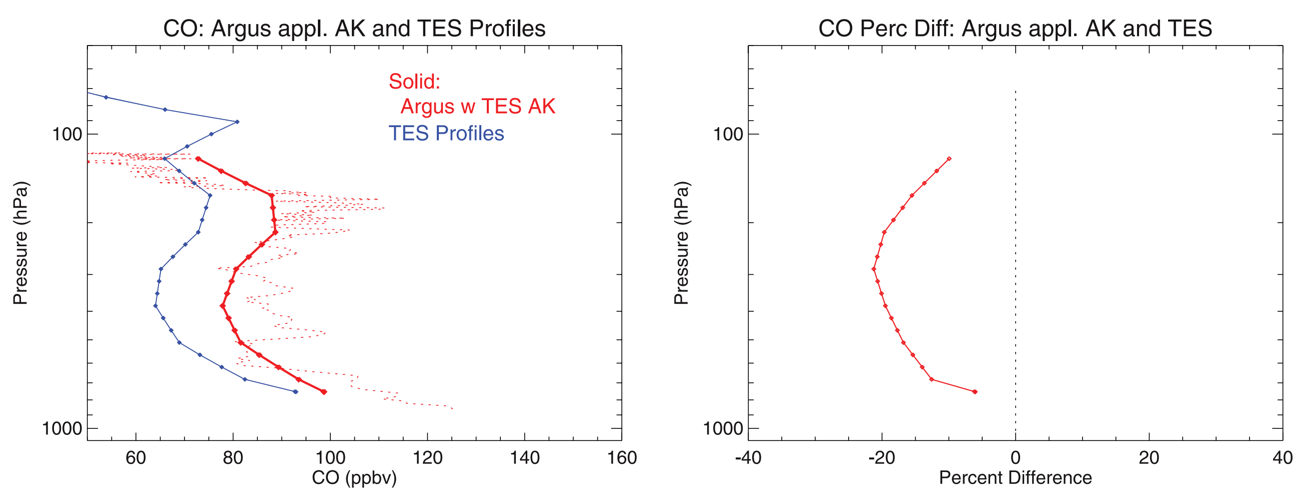

Figure 10. Argus and TES ascent profiles for the 20060209 flight. (left) The blue solid line is the TES profile. The red dotted line is the is the in situ high-resolution Argus CO profile and the red solid line is the Argus profile with the averaging kernel applied to the data. (right) The percent difference between

satellite retrievals and in situ measurements can be due to many reasons, including mismatches in locations and times.

[30] Figure 10 shows the comparison plots of Argus CO profile and TES retrieved CO profile for 9 February. The analysis of this flight was done in a similar fashion as for Oct-AVE and the previous CR-AVE flight mentioned. The TES cloud optical depth for takeoff was 4 at 645 hPa. With this layer of cloud, the TES retrieval has no information below it and the retrieved CO values are only meaningful above the cloud layer. The Argus CO profile, shown here, was obtained during takeoff, 87 km from the closest TES profile, which was separated by 13 h from the Argus measurements. Once the TES averaging kernel is applied to the CO Argus profile, the Argus CO profile is between 5 and 25% larger that the TES retrieved profile. The disagreement between the in situ CO profile and the TES retrieved CO profile may be due to a number of things. For one, the apparent thick could layer makes the TES retrievals more difficult. Second, while the closest TES profile was only 87 km away, it was temporally separated from the Argus in situ CO profile by 13 h. CO and the cloud coverage can change drastically, especially in the boundary layer, as the day progresses. Even with the poor absolute agreement, the shape of the retrieved TES profile and the Argus profile are quite similar, a typical tropical CO profile shape What is not captured in the TES CO retrievals is the actual CO variability seen in the high-resolution in situ data (both Argus and ALIAS). This is not unexpected with a small DOF in TES profile retrievals.

[31] Eleven aircraft ascent and descent profiles were used to compare ALIAS CO with TES CO retrievals (Table 2). Typical flight WB-57F flight profiles during CR_AVE consisted of southerly ascents over a large ($\sim$2°) latitude band followed by spiral descents at nearly constant latitude over San Jose, Costa Rica (9.9°N). TES retrievals were on average 430 km away, varying between 95 and 1060 km. As Table 2 summarizes, retrievals were generally conducted within 3 h of WB-57 measurements with the exceptions of 20060130, 20060209, and 20060211 where TES global survey retrievals were conducted 9 to 13 h before. An example of one flight, 20060209, is shown in Figure 11. Observation of higher CO on ascent versus descent is not unexpected. Ascent and decent occurred over different locations and times and given the spatial and temporal variability in CO at lower altitudes due to variations induced by pollution and variable meteorology, some difference is anticipated. There is evidence (shown in Figure 12 in the TES curtain plot for 17 January 2006; none is available for 9 February 2006 because TES was in GS mode) that elevated CO abundance at latitudes southward of 10°N, between 400 and 700 hPa, existed during CR-AVE because of biomass burning in the tropics. Thus, higher CO is expected to be encountered during the southerly ascents. For the flight with the least change in latitude during ascent, 20060117, ascent and descent agreed very well (to within $\pm$5 ppbv). Overall, both Argus and ALIAS observed higher CO during ascent during CR-AVE which became insignificant above 200 hPa where spatial variability of CO is diminished. Figure 13 directly compares ALIAS and TES CO profiles. Like Argus, ALIAS CO on ascent was noticeably higher than TES retrievals. In 500–200 hPa, ALIAS profile with TES averaging kernel applied was $\sim$20% higher than TES. On descent, TES-ALIAS compared very well with differences no more than 5%.

[32] Comparison plots of averaged Argus and ALIAS and TES profiles are shown in Figures 14 and 15, along with standard deviation of the differences at each pressure. The comparisons of Argus-TES and ALIAS-TES are consistent with TES CO being higher 5–10%. The correlation coefficients for the TES-Argus and TES-ALIAS comparisons are 0.47 and 0.4 respectively. By removing comparisons with over 1000 km apart between TES and the aircraft, these coefficients did not increase. Above about 100 hPa, where TES has nearly no sensitivity, both TES and the adjusted aircraft CO values follow the TES a priori profiles. The value of TES a priori CO at 90 hPa is higher than the unadjusted Argus and ALIAS values by more than 80% during the entire CR-AVE campaign as exemplified in Figures 9 and 13 (left, red dots).

9. Conclusion

[33] We have presented validation of TES CO retrievals with the in situ CO measurements taken by both Argus and ALIAS during two separate campaigns, Oct-Ave and CR-AVE. The two in situ observations of CO are found to agree typically within 4%. TES averaging kernels and a priori constraint profiles were applied to the in situ data before comparing to the TES data to account for much lower vertical resolution in TES CO retrievals. For Oct-AVE campaign based near Houston, October-November 2004, the averaged TES CO profiles are found up to 10% lower than the adjusted Argus in situ CO measurements. For CR-AVE campaign based near Costa Rica, January-February 2006, the averaged TES CO profiles are found 5–10% higher than the adjusted Argus and ALIAS measurements. The correlation coefficient for TES-Argus comparisons in Oct-AVE, after removing data with TES averaging kernel area less than 0.4, is 0.61. These results are similar to the comparisons found during INTEX-B [*Luo et al.*, 2007b]. The correlation coefficient however for the CR-AVE comparisons is 0.4, partly because of poor coincidences in location and time between TES and the in situ measurements. Overall, it was found that in the midtroposphere, TES CO is less than in situ CO in the midlatitudes near Houston, Texas, and is greater than in situ CO in the tropics near Costa Rica.

[34] In summary, up to four consecutive TES retrievals were used for comparison for each single aircraft profile. The aircraft profiles could span up to 250 km horizontally during takeoff or landing legs. The four TES nadir footprints cover about 170 km horizontally. An indication of CO variability during CR-AVE is shown in the TES retrieval curtain plot (only available for SS), with respect to latitude (Figure 12), for the 20060117 flight. WB-57F ascent and descent occurred about 460 km away from the TES measurements. Much of the small-scale (<1 degree) variability is expected to occur to the same extent with respect to longitude. This variability complicates comparisons of vertical profiles, as is the case in all the comparisons during the CR-AVE campaign. During the Oct-AVE campaign, the aircraft typically did spiral profiles for descents and consequently covered a smaller horizontal area, making better agreement.

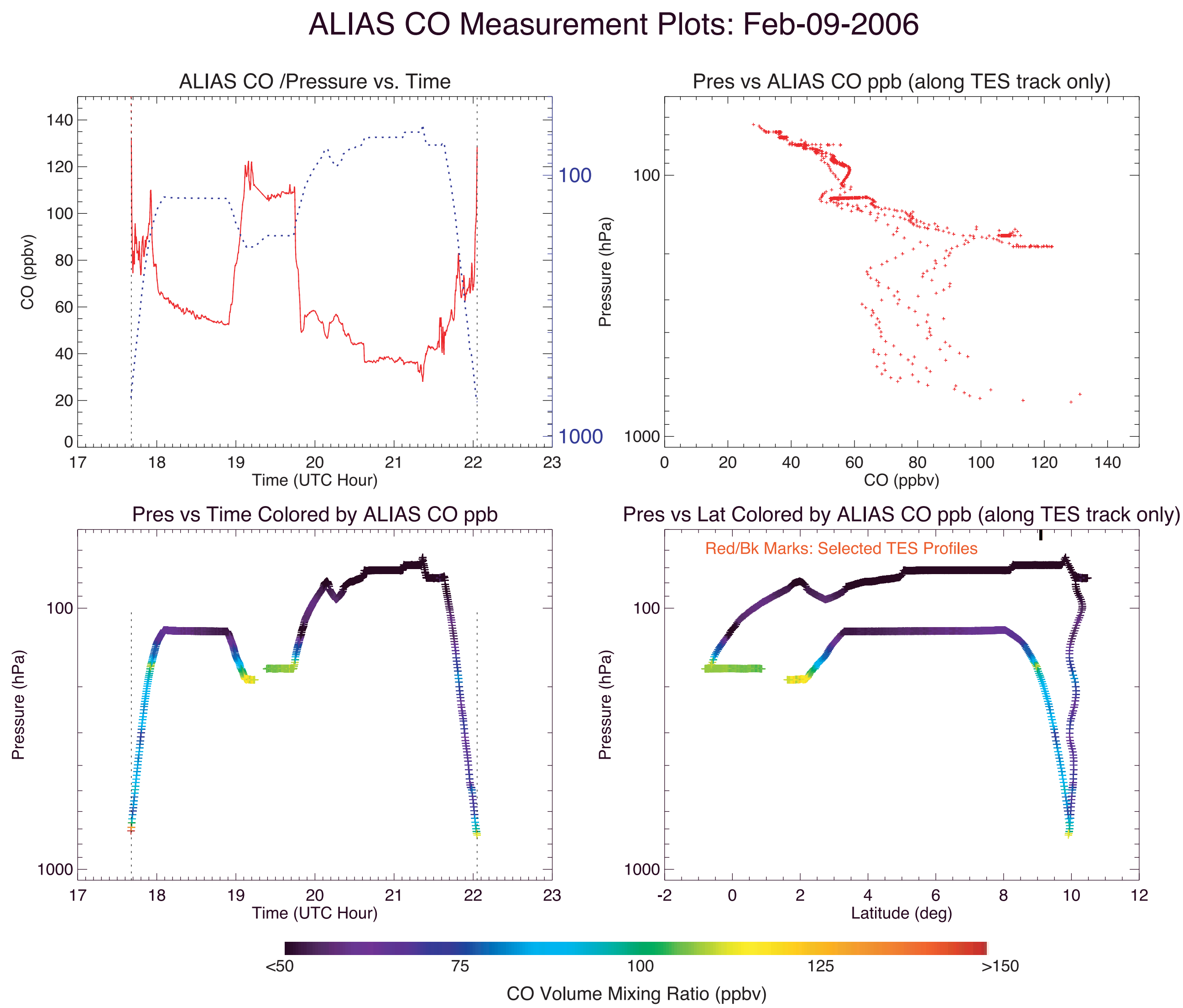

Figure 11. ALIAS measurement plots for flight 20060209. Difference between ascent and descent is attributed to differences in location and time: ascent occurred more southward of descent and likely encountered air containing higher amounts of CO (see text). Spikes in CO after 2130 UTC (above 80 hPa) are real and are due to the WB-57F flying through its own contrail, details readily observed by the high precision of ALIAS.

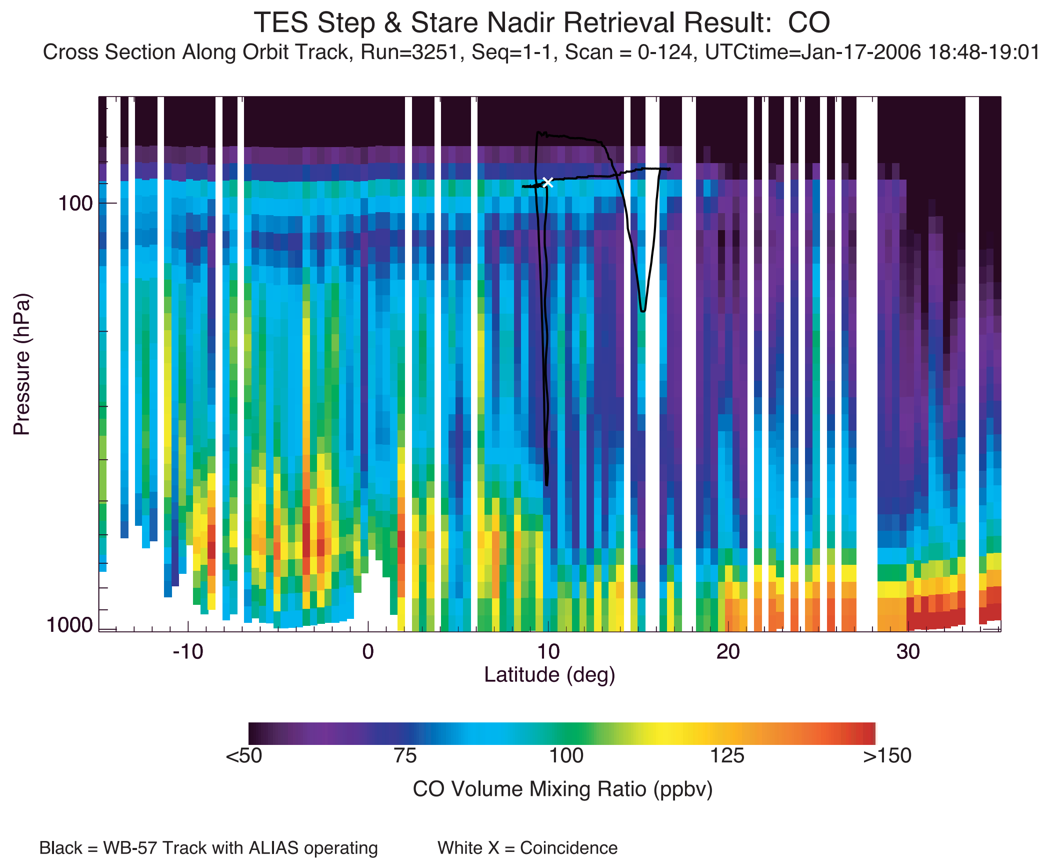

Figure 12. Latitude versus pressure curtain plot of TES CO retrievals taken in Step and Stare mode near San Jose, Costa Rica, 17 January 2006. Black line is the WB-57F flight path. White cross marks a coincidence in time and location.

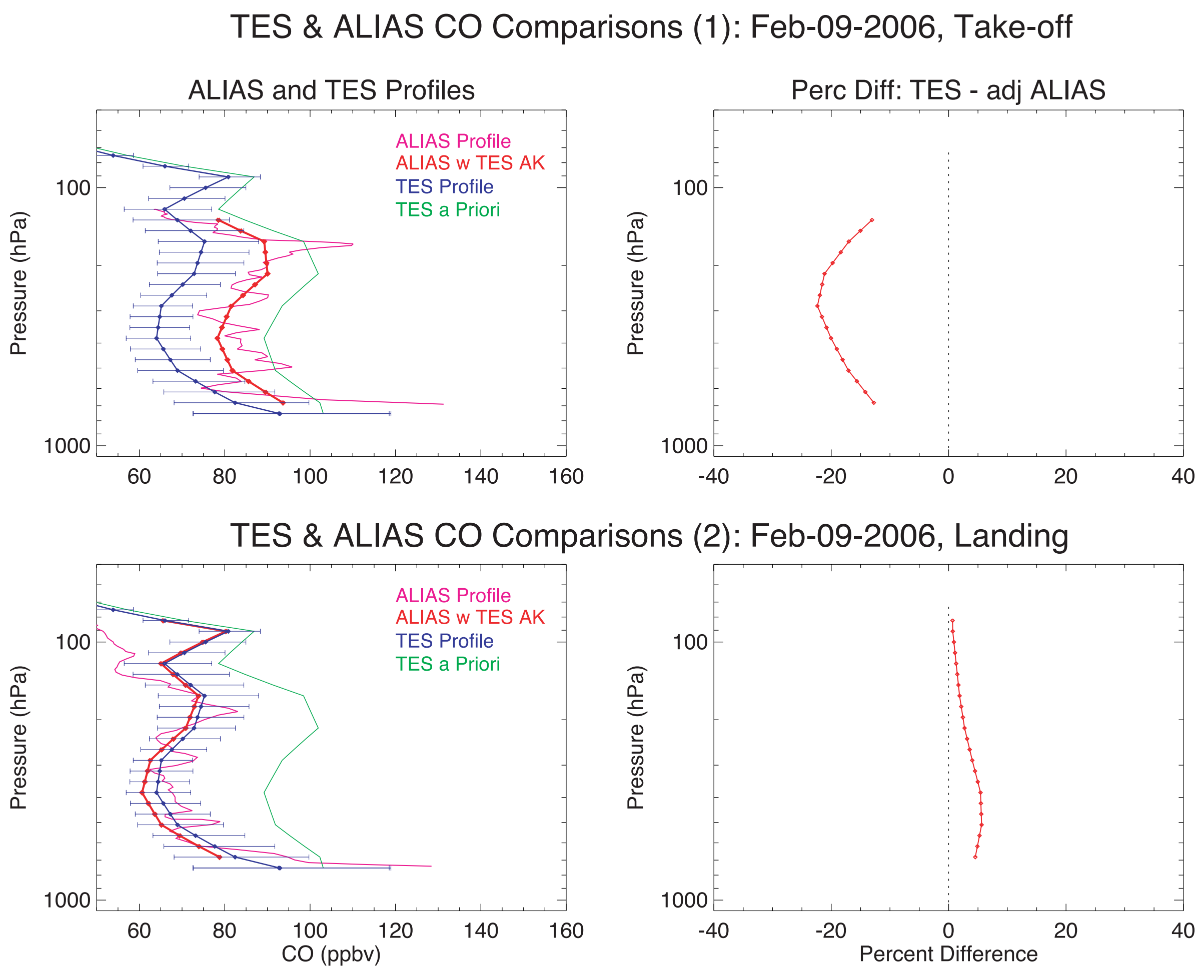

Figure 13. ALIAS and TES ascent (1) and descent (2) profiles for the 20060209 flight. The red line is ALIAS measurements. The blue line is the TES profile and horizontal blue lines are TES uncertainties. TES a priori is given in green.

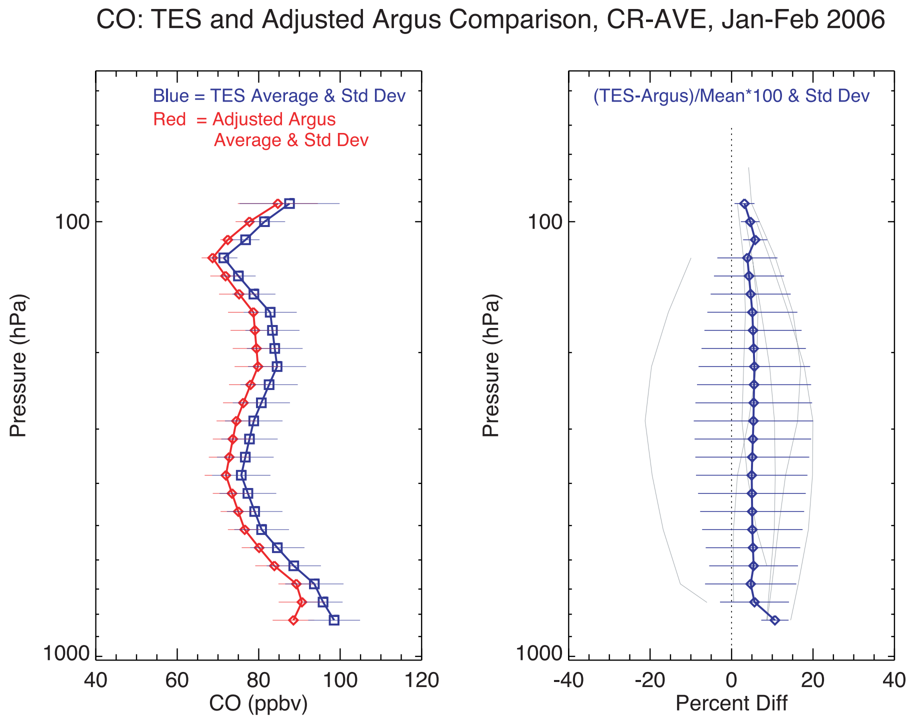

Figure 14. (left) Averaged Argus and TES CO and (right) difference profiles for CR-AVE campaign. The red line in Figure 14 (left) is the Argus data adjusted by the TES averaging kernel.

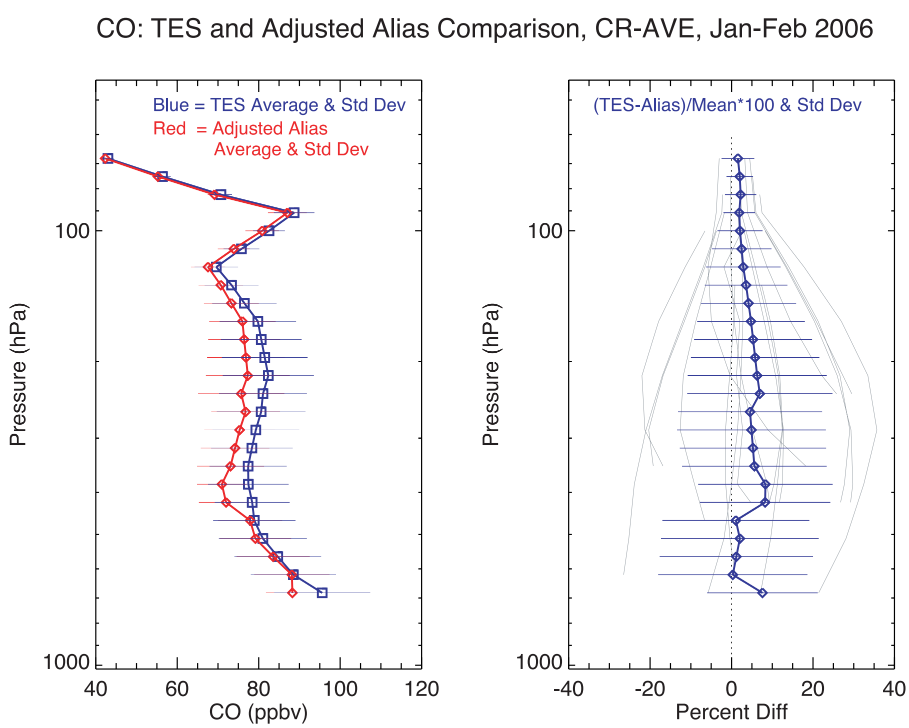

Figure 15. (left) Averaged ALIAS and TES CO and (right) difference profiles for the CR-AVE campaign. The red line in Figure 14 (left) is the ALIAS data adjusted by the TES averaging kernel.

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